/CDF/ANAL/EXOTIC/CDFR/7090

Searches for First Generation Leptoquarks in the eνjj channel

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Abstract

This note describes the analysis update for search for first generation scalar leptoquarks.

The full CDF dataset up to the Summer shutdown of 2003 has been used, corresponding to about 200.0 pb^{-1} of run II data taken at $\sqrt{s}$ = 1960 GeV. The data have been reprocessed with software version 4.11.1 (REMAKE sample) and the signal efficiencies and background estimate has been revised and/or updated.

Leptoquarks are assumed to be pair produced and to decay into a lepton and a quark of the same generation. We will focus on the signature represented by one energetic electron, missing energy and two jets. We set an upper limit at 95% CL on the production cross-section as a function of the mass of the leptoquark.
Assuming (β = Br(LQ$\rightarrow$ eq)) = 0.5 and using the NLO theoretical estimate we reject the existence of scalar leptoquarks with mass below 178 GeV/c^2 .

Introduction

A common feature of theoretical models trying to imagine possible scenarios for new physics is the symmetry between quarks and leptons suggested by the Standard Model, and the search for a more foundamental relation between them. Theories like Grand Unification and R-parity violating Supersymmetry introduce the idea of quark to lepton transitions, therefore suggesting that particles carrying both lepton and baryon number exist. Among the rich fauna of exotic particles, leptoquarks are of special interest as they could be the mediator of this new kind of lepton-quark interaction.

Leptoquarks are hypothetical color-triplet particles carrying both baryon and lepton quantum numbers and are predicted by many extension of the Standard Model as new bosons coupling to a lepton-quark pair. Their masses are not predicted. They can be scalar particles (spin 0) or vector (spin 1) and at high energy hadron colliders they would be produced directly in pairs, mainly through gluon fusion or quark antiquarks annihilation. The couplings of the leptoquarks to the gauge sector are predicted due to the gauge symmetries, up to eventual anomalous coupling in the case of vector leptoquarks, whereas the fermionic couplings are free parameters of the models.
In most models leptoquarks are expected to couple only to fermions of the same generations because of experimental constraints as non observation of flavor changing neutral currents or helicity suppressed decays. At the TeVatron leptoquarks would be pair produced and would decay into a lepton and quark of the same generation. Traditionally the branching ratio describing the decay of the leptoquark into a charge lepton and and quark is called □.
In figure 1 a typical production diagram is reported.

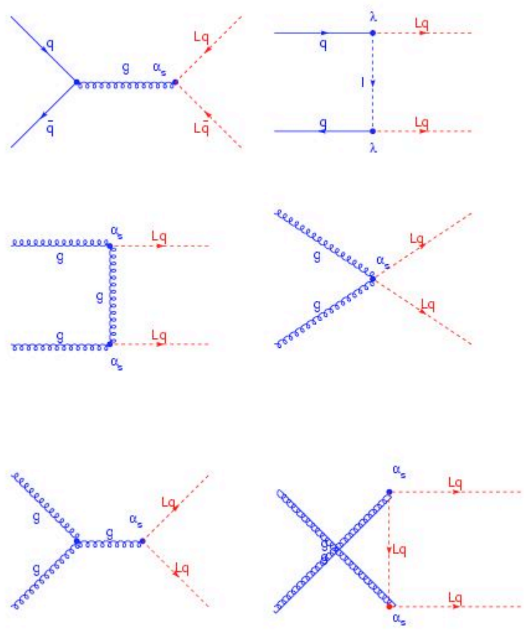


Figure 1

The production cross section for pair produced scalar LQ has been calculated up to NLO[1].The decay angular distribution of scalar leptoquarks is isotropical. The NLO cross section at s = 1960 GeV is reported in Table 1 for values of the LQ mass between 200 and 320 GeV/c^2. The scale has been chosen to be $Q^2 = M_{LQ}^2$ and the set of parton distribution functions is CTEQ4M[].

M_{LQ} (GeV/c^2)	σ(NLO) [pb]
200	0.265E+00
220	0.139E+00
240	0.749E-01
260	0.412E-01
280	0.229E-01
300	0.129E-01
320	0.727E-02

Table 1 –*Theoretical cross section for pair production of LQ at $\sqrt{s}$ = 1960 GeV. Q = m(LQ)*

The cross section compared with the one at 1.8 TeV is reported in Figure 2

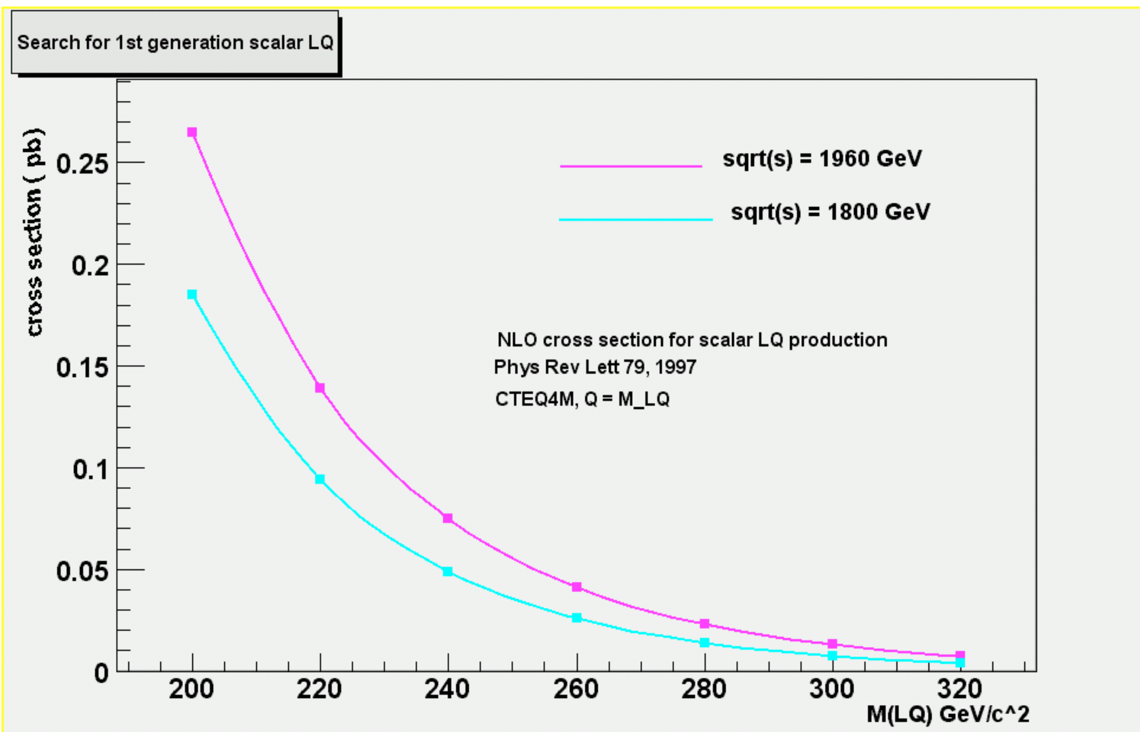


Figure 2

This analysis is focused on the search for first generation scalar leptoquarks S1, pair produced and decaying into $e\nu jj$. The result presented in the current note is an update of the one presented in note [2]. A few modifications have been introduced in respect to [2], in particular the missing E_T significance cut has been abandoned in favor of a cut around the nominal leptoquark masses, to optimize background rejection and obtain the best limit. This approach was originally pursued in the Run I analysis[3] and we followed the same procedure outlined there.

Current Limits

In table 1 the current limits on the first generation LQ are reported, both from CDF and D0.

1st Gen	□	Scalar (GeV/c^2)
D0	1 0.5 0	238 198 98 (Run I)
CDF	1 0.5 0	230 166 117

Table 2 – *current limits on first generation LQ from the TeVatron*

Data sample and electron identification

The data sample used for this analysis is *btop0g* (inclusive electrons) stripped for the Top group from the inclusive high pt electron datasets. The sample is described in[4].
The L3 trigger dataset *(bhel08*) was reconstructed with offline version 4.8.4 and the events were filtered into *btop0g* using the following loose cuts:

- CdfEmObject.Pt > 9.0 GeV
- CdfEmObject.etCalMin > 18.0 GeV
- CdfEmObject.delX < 3.0
- CdfEmObject.delZMin < 5.0
- CdfEmObject.E/P < 4.0
- CdfEmObject.lshr < 0.3
- CdfEmObject.hademMax < 0.125

For the ELE_70 trigger:

- CdfEmObject.Pt > 15.0 GeV
- CdfEmObject.etCalMin > 70.0 GeV
- CdfEmObject.delX < 3.0
- CdfEmObject.delZMin < 5.0

A REMAKE version of *b0topg* was made where all the calorimeter-dependent objects were dropped in input as well as electron and muon reconstruction objects. The 4.8.4 tracks were refitted (using TrackRefitModule) without L00 hits, and electron and muon

objects were remade picking up the refit tracks and run-dependent calorimeter corrections. The sample is described at http://www-cdf.fnal.gov/internal/physics/top/topdata/TopData_4111.html and corresponds to an integrated luminosity of 199.7 * 1.019 pb^{-1} (good runs between March 2002 and September, 2003 – runs 141544 to 168889) , selected following the *good run list without Silicon for electron*, version 4, as described in http://www-cdf.fnal.gov/internal/dqm/goodrun/v4/goodv4.html).
As for the Z’ analysis, both the Electron_Central_18 and Electron_70 triggers were used, due to the complementary efficiency of the had/em cut.

The sample has been reduced by requiring events with at least 1 CdfEmObject satisfying the following criteria:

- $E_T > 25$ GeV
- $p_t > 15$ GeV
- hadem < 0.055 + 0.00045 * E
- E/p < 4 (for $E_T < 100$ GeV)
- |DeltaX | < 3.0 cm
- |DeltaZ | < 5.0 cm
- lshr <= 0.2
- FIDELE == 1
- isolation ratio < 0.1 (0.2 for loose electrons)

We veto events with a second loose (iso < 0.2) central electron or a second plug electron satisfying the ID cuts reported here:

- $E_T > 25$ GeV
- isolation ratio < 0.1
- $E_{had}/E_{em} < 0.055 + 0.00045 * E$
- $\chi^2_{3x3} < 10$
- Fiducial cut 1 < $|\eta|$ < 3

In this way we ensure that our final data sample is orthogonal to the sample used in the eejj analysis, where we searched for first generation LQ in the case where both LQ’s decay into electron and quark. We apply the second electron veto on the signal MC as well as the background (where obviously the presence of a second electron is an artifact of reconstruction, since at the generation level we generate only processes with one electron). In this way however we ensure that at the time of combining the result of different channel, our efficiency will be calculated on clearly separated samples.

These electron identification cuts we use are used in the Z’[5,6] analysis as well as adopted as official cuts from the Exotic group. The efficiencies are reported in Table 3.

CDF Run II Preliminary (200 pb^{-1})

Cut	Number of candidate events	Number of background	Efficiency (%)
$Iso < 0.1$	4686	146	97.2± 0.2
$Iso < 0.2$	4912	204	99.0± 0.1
$E_{had}/E_{em} < 0.055 + 0.00045 \times E$	4962	252	99.0± 0.1
$E/P < 4.0$(for $E_T < 100$)	5357	562	99.9± 0.0
$\|\Delta X\| < 3.0$	5210	508	98.9± 0.1
$\|\Delta Z\| < 5.0$	5299	532	99.7± 0.1
$L_{shr} < 0.2$	4988	304	98.7± 0.1
Tight central overall(ε_T)	4406	108	94.5± 0.2
Tight central overall(ε_L)	4569	120	96.2± 0.2
$\varepsilon_{CC}(= 2 \cdot \varepsilon_T \cdot \varepsilon_L - \varepsilon_T^2)$			92.4± 0.4

Table 3 – *Efficiency for CC electrons as from ref[5,6]*

Acceptance calculation

We generated 5000 events samples of scalar leptoquarks pair decaying one into eq and the other into □q for M_{LQ} in the range 100 to 280 GeV/c^2 using Pythia[10]. The samples have been generated to simulate realistic beam conditions, emulating run number 151435 and using the following talk-to for the full beam position:

```
talk GenPrimVert
  BeamlineFromDB set false
  sigma_x        set  0.0025
  sigma_y        set  0.0025
  sigma_z        set 28.0
  pv_central_x   set -0.064
  pv_central_y   set  0.310
  pv_central_z   set  2.5
  pv_slope_dxdz  set -0.00021
  pv_slope_dydz  set  0.00031
exit
```

The samples were generated with $Q^2 = M_{LQ}^2$ and the MRS-R2 pdf set[12]. The samples were simulated with cdfSim version 4.9.1 and Production 4.9.1 was ran on them.
In figure 3-5 the E_T distributions of the decay products of the Leptoquark are plotted, for different values of the mass of the leptoquark and compared to the major sources of background.

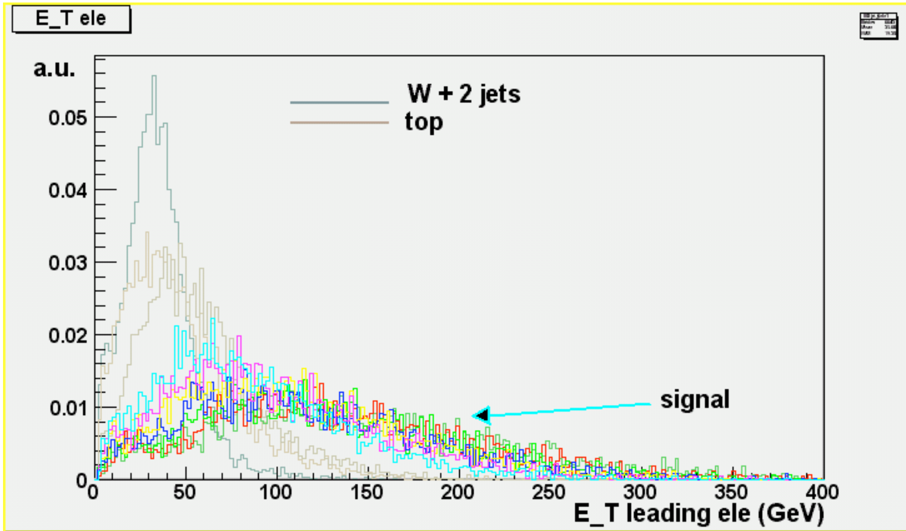


Figure 3 – E_T distribution of the electron, signal vs background

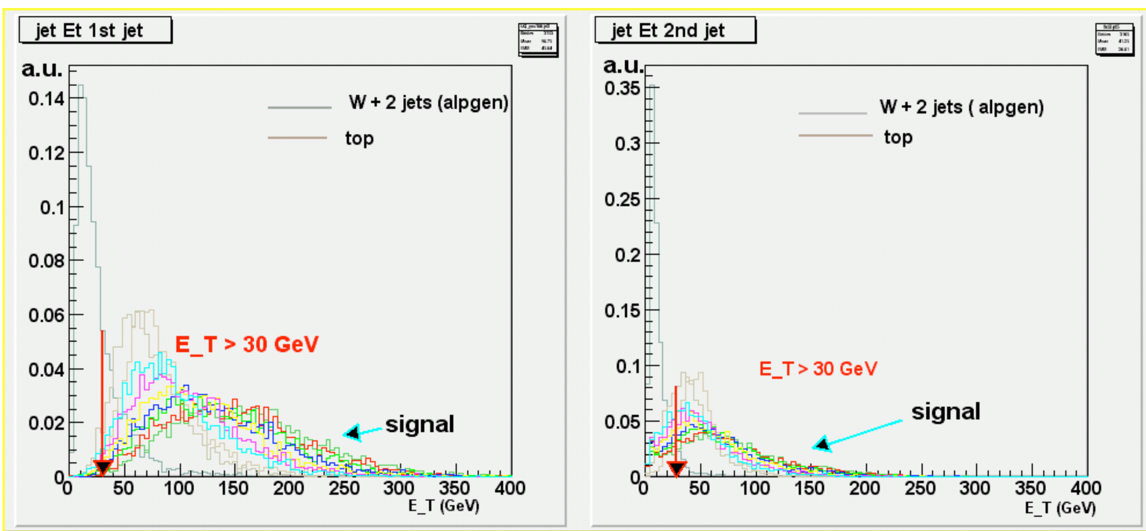


Figure 4 – E_T distribution of the two leading jets, signal compared to background

Our final event sample is selected in the following way:

- 1 electron with $E_T > 25$ GeV , satisfying tight central ID cuts;
- veto on second central tight/loose or plug electron;
- Missing Energy (corrected for jets) > 60 GeV
- 2 central jets with $E_T(j1) > 30$ GeV
- $\Delta\phi$ (MET-jet) > 10°
- $E_T(j1) + E_T(j2) > 80$ GeV
- $M_T(e\text{-}\nu) > 120$

- 3□ cut around the nominal LQ mass

The analysis cuts efficiencies are calculated relatively to the number of events having one reconstructed electron matched to the HEPG electron from the decay of the LQ.

We apply electron ID cuts as well as a fiduciality requirement, in order to be able to reject a second loose/plug electron. Since the ID efficiency of MC and data are different, a scale factor between data and MC is derived by comparing the ID efficiency of the MC for each type of process to those of the data (Table 4).

Cuts	**Cdf 6746**	**W + 2 jets**	**m(LQ) = 200**
Iso < 0.1	97.2 ±0.2	95.7 ±0.2	95.7 ±0.2
Had/EM	99.0 ±0.1	99.9 ±0.2	99.5 ±0.2
E/P	99.0 ±0.1	97.29 ±0.2	96.8 ±0.2
Dx	98.9 ±0.1	98.9 ±0.2	98.4 ±0.2
Dz	99.7 ±0.1	99.3 ±0.2	98.9 ±0.2
lshr	98.7 ±0.1	98.6 ±0.2	98.9 ±0.2
□T	94.5 ±0.2	89.9 ±0.2	88.1 ±0.2

Table 3- Individual ID cuts efficiency from data (cdf6746) and MC (W + 2 jets and LQ_200)

The kinematical and geometrical efficiencies are then multiplied by the scale factor between data and simulation, and folded with the z vertex cut efficiency[7] (0.952 ±001 (stat) ±005 (sys)) and the trigger efficiency[8] (0.991 ±001) .

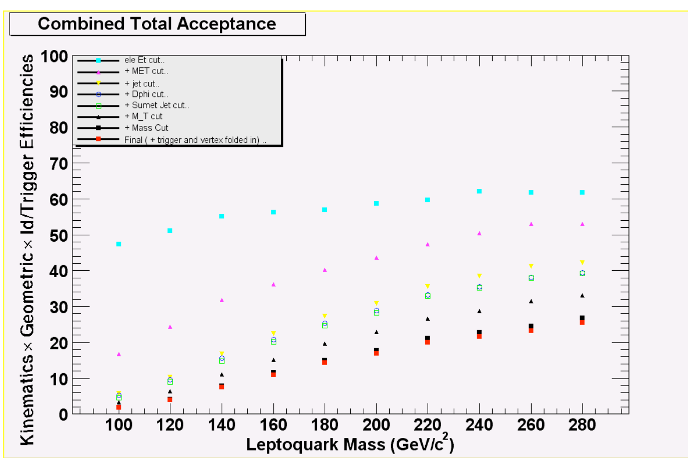


Figure 4 – *Final signal efficiency as function of the leptoquark mass*

The expected number of signal events in 203 pb^{-1} are obtained using the above efficiencies and the NLO theoretical cross section for different value of the renormalization/factorization scale, is reported in the Table below:

Mass (GeV/c^2)	n Theory CTEQ4M (pb) $Q^2 = M^2_{LQ}/4$	n Theory CTEQ4M (pb) $Q^2 = 4M^2_{LQ}$
100	35	26.5
120	27	21
140	21	16
160	13.5	10.5
180	8.5	7
200	5.2	4.2
220	3.2	2.6
240	1.65	1.5
260	1.1	0.9
280	0.65	0.5

Table 5 – *Expected number of signal events in 203 pb^{-1}*

After our selection cuts 18 events are left before the mass combination cut. In Table 6 we report the number of events surviving each kinematical cut. In the next sections we will describe the major sources of background and the final mass combination cut.

Number of events with one tight electron and MET > 60 GeV	1073
2 jets with E_T > 30 GeV	125
□□(MET-jet) > 10°	104
E_T(j1) + E_T(j2) > 80	95
M_T (e-□) > 120 GeV/c^2	18

Table 5 – *List of events passing the selection cuts*

Backgrounds

The main background is due to *W□ e□* events accompanied by jets due to radiation. The main component of this background is eliminated by cuts on M_T of the electron and neutrino. We studied the distribution of this background by generating the process *W + 2 jets* with Alpgen[11] and using the MC parton generator mcfm[13] to obtain the NLO cross section. The sample used is *atop02* where we processed 120k events.
Another source of background is represented by tt production where both the W decay into e□ and one lepton is mismeasured or one of the W decay leptonically and the other hadronically (lepton + jets).

We used 20K events from *ttopei* sample.
A small source of background is represented by *Z + 2 jets*, where one of the electrons is misidentified . This sample has been generated with Alpgen as well and HERWIG as parton shower.
The background from *$W \to \tau\nu$ + 2 jets* has been calculated to be negligible. We used *atop2e* sample (150K events).
To normalize simulated events to data we used the central value of the theoretical cross section for tt, σ(tt) = 6.7 pb , and the theoretical cross section for W + 2 jets and Z + 2 jets from mcfm (294 pb for W + 2 jets $\times$ Br ($W \to l\nu$) and 98pb for Z + 2 jets $\times$ Br ($Z \to ll$)).

Leptoquark mass reconstruction and final event selection

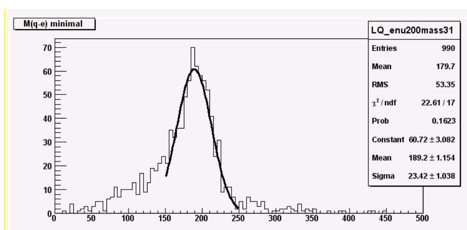
Eventually we want to set leptoquark cross section and mass limit based on the theoretical predictions of the LQ pair production cross section as a function of the leptoquark mass. In the previous analysis[2] we used a *missing E_T significance* cut that greatly reduced the background contribution from W + 2 jets and top. However, this cut presents some intrinsic weakness, as it is strongly dependent on the definition of Sumet and unfortunately on its mis-modeling in MC. One obvious effect is that in general Sumet is smaller in MC data than in real data and as such the efficiency of a cut which uses Sumet as denominator is overestimated on MC than in data. One can solve this issue introducing a (more or less) large systematic uncertainty in the final acceptance estimate, but after some study we conducted using the missing E_T significance and the LQ mass reconstruction we concluded that the limit would have been better estimated using this last approach. Indeed the amount of background expected and the signal acceptance stay the same in both approaches, but in the hypothesis that in the data there is no signal, the mass cut is the ideal way to isolate background from signal as the data (assumed to be composed of background) will lay in a random way in respect to the preferential position around the LQ mass.

To select leptoquark candidates of a given mass we followed the procedure outlined in cdfnote 4228[3]. We built the *invariant mass* of the *electron-jet* system and the *transverse mass* of the *neutrino-jet* system.
Given the decay of the two LQ's, there are two possible mass combinations for the electron and the neutrino with the 2 leading jets. As in cdf 4228 we have chosen the masses that minimize the difference between the electron-jet mass and the neutrino-jet transverse mass. This algorithm was shown to yield a smaller root mean square in the reconstructed mass distributions than if we had simply cumulated the two possible combinations.
Then we fitted the peak of the *ej* distribution with a Gaussian, to obtain a rough estimate of the spread of the distribution in the signal region. We did this exercise for several LQ mass (120-160-200-240-280) and concluded that the spread σ_e is on average 15% (

increasing with the LQ mass). We then operate a $3\sigma_e$ cut around the nominal leptoquark mass to select leptoquark candidates of a given mass. The νj transverse mass distribution is also fitted with a Gaussian, taking into account its high tail. The spread σ_ν is thus found tipically to be on average 25% of the leptoquark mass (increasing with the LQ mass). One could argue that this significantly reduces the signal efficiency in the low side of the signal region, however the lower νj transverse mass region is also more populated by the background.
In the end, those 3σ mass cuts can be represented by boxes in the 2-dimensional plane defined by the invariant mass ej and the transverse mass νj.
The way the data distribute in the 10 LQ boxes corresponding to the masses we probed is reported in table 6.

Mass	**100**	**120**	**140**	**160**	**180**	**200**	**220**	**240**	**260**	**280**
W+2 jets	1.5±0.9	1.5±0.9	1.5±0.9	2.5±1.13	2.5±1.13	2.5±1.13	2.0±1.0	2.0±1.0	1.5±0.8	0.5±0.1
top	2.5 ±0.6	3.08 ±0.6	2.9 ±0.6	2.6 ±0.6	2.3 ±0.5	1.8 ±0.5	1.5 ±0.3	1.0 ±0.3	0.7 ±0.2	0.6 ±0.2
Z+jets	0.05±0.01	0.05±0.01	0.08±0.02	0.08±0.02	0.08±0.02	0.08±0.02	0.06±0.02	0.06±0.02	0.04±0.01	0.04±0.01
Total	4.2±3.8	4.65 ±4.3	4.5 ±4.0	5.16 ±4.3	4.85 ±4.0	4.47 ±3.8	3.6 ±3.2	3.1 ±2.8	2.3 ±2.1	1.1 ±1.1
Data	**7**	**7**	**6**	**6**	**4**	**4**	**4**	**2**	**2**	**1**

Table 6 – Expected signal after the final mass cut and data observed



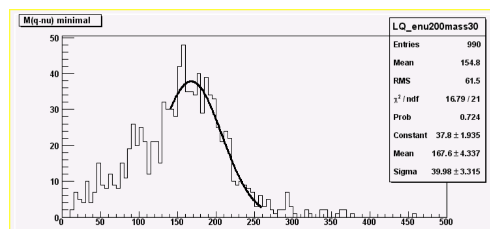


Figure 5 - Reconstructed mass and transverse mass of the lepton-jet system for M(LQ = 200 GeV/c^2

W cross section check

We did check that the events we are left before requiring 2 jets and the subsequent analysis cuts are consistent with the production of W.
W boson candidates are selected by relaxing the MET cut to 25 GeV (so that we can compare to the official W cross section analysis[9]) and the cross section is calculated from the following formula:

$$\sigma \times Br\,(p\bar{p} \rightarrow W \rightarrow \nu e) = (N_W - N_{BG})/(A_W \times \varepsilon_{ID} \times \varepsilon_{trig} \times \varepsilon_{z0} \times R_{COT} \times R_{EMC} \times \mathcal{L})$$

Using the values listed in the Table below (cdfnote 6681[9], extrapolated to the increased luminosity) we obtain for the W cross section a value of

2.953 ± 31.7 (stat) $\pm$ 51.0 (sys) $\pm$ 177 (lumi) nb.

Acceptance	23.895 ± 0.03 (stat) ± 0.35(sys) %
ID efficiency	81.8 ± 0.8 ± 0.2 %
Trigger Efficiency	96.6 ± 0.1%
z_0 efficiency	95.2 ± 0.5%
R_{COT}	100.0 ± 0.4%
R_{EMC}	99.8 ± 0.4%
Observed number of events	**112384**
Estimated background	1656 * 203/72
Integrated Luminosity	203 ± 0.06*203

Table 7 – *parameters used in the calculation of the W cross section*

We also checked that we predict the right number of W + 2 jets. To this extent we counted events after the 2 jets requirement, but relaxing the MET cut to 35 GeV. The QCD background (corrected for sideband contributions) is 38.5 ± 6 events, the top contribution 56 ± 8, Z + 2 jets contribution ~25 ± 3 and W□ □□contribution 16.6 ± 2.6. The total background is then 136.5 ± 20. The number of expected W + 2 jets from Alpgen is 366 ± 17. We observe 536 events, in agreement with the expectation.

In Figure 6 we report the E_T spectrum of the 2 leading jets, compared with the SM expectations (QCD background not included).

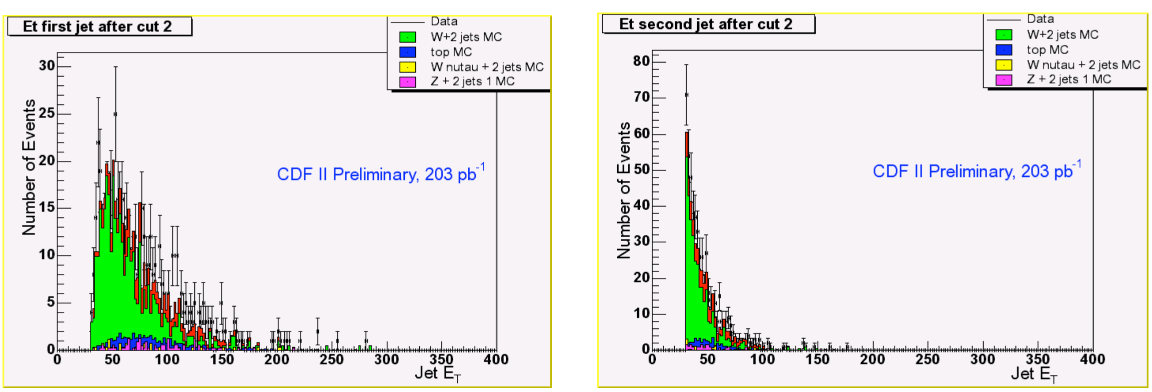


Figure 6 – *Jet E_T distribution for MC and data. Data and generated MC have been normalized to each other to take into account the different luminosity. 2 jets requirement is applied and no subsequent LQ analysis cuts.*

Systematic Uncertainty

The following systematic uncertainty is considered:

- Luminosity: 6%
- Acceptances
  - pdf 4.3% (from run I)
  - statistical error of MC 2.2%
  - Jet energy scale < 1%
  - ID scale factor 0.06%
- Event vertex cut : 0.5%[7]
- ISR/FSR 1.7% (from dilepton[10] analysis)

Cross section Limit

The production cross section σ of the process $LQLQ \rightarrow e\nu jj$ can be written as follows:

$$\sigma \cdot 2 \cdot Br(LQ \rightarrow ej)(1 - Br(LQ \rightarrow ej)) = \sigma \cdot 2 \cdot \beta \cdot (1-\beta) = N/(\varepsilon \cdot L),$$

where N is the number of observed events on data after our selection, ε is the total selection efficiency as a function of M_{LQ} and L is the integrated luminosity. As we found candidate events in our final selection, we set a 95% C.L. upper limit on the cross section as a function of M_{LQ} defined as:

$$\sigma^{lim} = N^{lim}/(\varepsilon \cdot L \cdot 2 \cdot \beta \cdot (1-\beta))$$

The limit was calculated using the bayes code[14].
In Figure 12 the limit cross-section as function of M_{LQ} is compared with the theoretical expectations for $\beta = 0.5$. At the intersection point between experimental and theoretical curves we find the lower limit on M_{LQ} at 178 GeV/c^2.

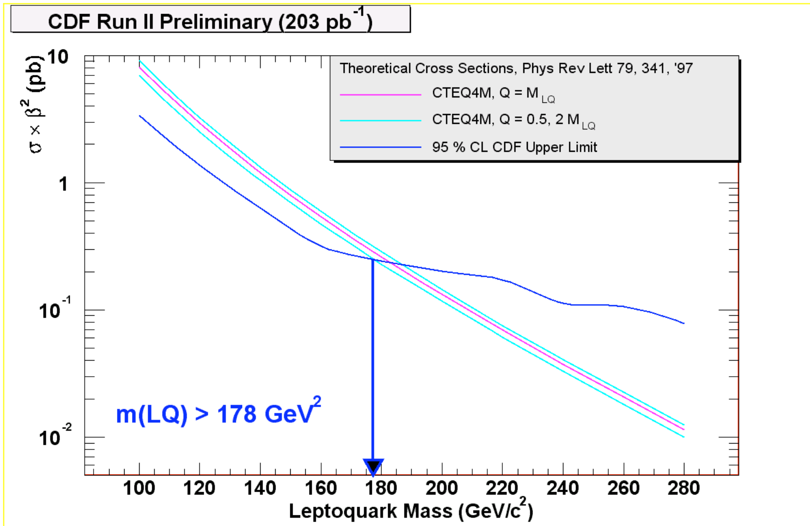


Figure 12- *Limit cross section as a function of M_{LQ} compared with the theoretical expectations calculated at NLO accuracy. At the intersection points between experimental and theoretical curves we find a lower limit on M_{LQ} at 178 GeV/c^2*

Conclusions

We have presented a preliminary 95% CL cross section lower limit as a function of M_{LQ}, for leptoquarks decaying with 50% branching ratio into eq and we have compared it to the theoretical predictions for leptoquark pairs production at the TeVatron. By using the theoretical estimate, we can reject the existence of a scalar leptoquark with mass lower than 178 GeV/c^2 for □ = 0.5

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10) Measurement of the $\sigma \cdot Br(W \to e\nu)$, $\sigma \cdot Br(Z \to ee)$, and the ratio R using CDF Run II Data, Dan Amidei et al. CDF/DOC/ELECTROWEAK/CDFR/6711
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12) http://mlm.home.cern.ch/mlm/alpgen/
13) http://consult.cern.ch/writeup/pdflib/
14) http://mcfm.fnal.gov/
15) Poisson Upper Limits Incorporating Uncertainties in Acceptance and Background John Conway Kaori Maeshima
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